QoS-based Power Control and Resource Allocation in OFDMA Femtocell Networks

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***Abstract*—This paper proposes a new joint power control and resource allocation algorithm in OFDMA femtocell networks. We consider both QoS constrained high-priority (HP) and best-effort (BE) users having different types of application and bandwidth requirements. Our objective is to minimize the transmit power of each femtocell, while satisfying a maximum number of HP users and serving BE users as well as possible. This optimization problem is multi-objective NP-hard. Hence, we propose a new scheme based on clustering and taking into account QoS requirements of users. We show by extensive network simulation results that our proposal outperforms three state of the art schemes (Centralized-Dynamic Frequency Planning, `C-DFP`, Distributed Random Access, `DRA` and Distributed Resource Allocation with Power Minimization, `DRAPM` as well as our previous proposal, `FCRA`, in both low and high density networks. The results concern the rate of rejected users, the throughput satisfaction rate, the spectrum spatial reuse, fairness, as well as computation time.**

***Index Terms*—Femtocells, OFDMA, QoS, power control, resource allocation, clustering, performance evaluation.**

I. INTRODUCTION

Mobile broadband services have recently grown considerably. Affordable high speed services are the driver behind the increase of new generation mobile devices and smartphones. However, coverage and capacity problems pose some limitations for time-sensitive applications such as VoIP, video on demand and online games, which need high speed and low latency. While reducing the financial cost per bit, operators need to ensure a good coverage and high system capacity to deliver these services. OFDMA femtocells (with LTE and LTE-advanced access technologies) arise here as potential solution that answers the two major problems. First, femtocells improve the coverage in indoor environments, where most of the data and voice traffic takes place [1]. Secondly, femtocells increase system capacity and spatial reuse by reducing cell sizes and offloading macrocells.

Femtocells are deployed within the vicinity of end users and are connected to the operator's network through a broadband connection (e.g, ADSL, fiber, etc.). The deployment of femtocells in the underlying macrocell network gives rise to co-layer and cross-layer interference. When femtocells use different frequency bands than macrocells (i.e., split-spectrum approach), the cross-layer interference is avoided and femto-to-femto interference remains the major issue. In particular, congestion cases in which femtocell demands exceed the available bandwidth pose an important challenge. In this context, we propose a new joint power control and resource allocation algorithm, called `QP-FCRA`, in OFDMA femtocell networks. `QP-FCRA` relies on our previous work [2], where we proposed a cluster-based resource allocation algorithm for OFDMA femtocells, without taking into account quality of service (QoS) differentiation between users and with a fixed transmit power for each Femtocell Access Point (FAP). In this paper, we extend our previous proposal [2] and introduce a power control strategy aiming at minimizing the sum of transmit power for all users within the FAP, and at the same time support QoS. Indeed, since operators would offer different data plans, with services and applications having different requirements, two types of users are introduced: i) high-priority (HP) users with fixed QoS requirements, who want to pay more in exchange for a better QoS, and ii) best-effort (BE) users having different types of applications, requiring less resources and can be charged accordingly. Our objective is thus to associate the best spectrum set of frequency/time resources and transmit power with each femtocell user in order to fully satisfy HP users and serve as well as possible the BE users. To achieve this, we formulate the joint power control and resource allocation problem as a multi-objective optimization problem. The first objective is to minimize the transmit power while guaranteeing both the required Signal to Interference plus Noise Ratio (SINR) and demands for HP users. The second objective is to allocate as well as possible the remaining resources to BE users.

We compare the `QP-FCRA` algorithm with three prominent existing strategies: Centralized-Dynamic Frequency Planning `C-DFP` [3], Distributed Random Access `DRA` [4] and Distributed Resource Allocation with Power Minimization, `DRAPM` [5] as well as our previous work `FCRA` [2]. Evaluation and comparison metrics include the rate of rejected users, the satisfaction rate of required throughput, the spectrum spatial reuse, fairness, and computation time. The obtained results show the improvement of `QP-FCRA` over the existing approaches in both low and high density environments and under various interference scenarios.

The remainder of this paper is organized as follows. Section II presents an overview of the related works. In Section III, we present the system model and formulate our joint power and resource allocation problem. Section IV introduces the `QP-FCRA` algorithm, followed by a description of the evaluation metrics in Section V. Simulation results are presented in Section VI. Finally, Section VII concludes this paper.

II. RELATED WORK

In the literature concerned with the resource management in OFDMA femtocell networks, two main directions are evidenced: i) shared spectrum and ii) split-spectrum schemes. With shared spectrum approach [6]–[8], coordination or localization mechanisms between femtocells and macrocells are needed to manage cross-layer interference (interference between macrocell and femtocells). Such mechanisms may add scalability and security issues, and may be counterproductive whether there is limited availability of backhaul bandwidth [9]. A protocol model and random conflict graph have been used in [10] to describe the spectrum reuse problem. The authors have derived upper and lower bounds on the number of resource blocks required to satisfy minimal requirements for both split spectrum and shared spectrum schemes. In our case, we consider an orthogonal channel assignment as in [3]–[5], [9] and where we focus on co-layer interference mitigation between femtocells.

Authors in [3] propose a centralized resource allocation, called `C-DFP`. Such a scheme introduces a high computational complexity, which affects the system scalability and therefore it cannot be applied to dense environment scenarios.

In [4], the authors proposed a distributed resource allocation algorithm, called `DRA`. The resources are split between macrocells and femtocells based on the gradient ascent/descent heuristic. Then, each femtocell runs locally `DRA` to reserve a set of resources using a randomized hashing function. To do so, each femtocell divides the resources into blocks proportional to the number of interfering neighbors.

Similarly, the authors in [9] propose a decentralized `Frequency-ALOHA` allocation strategy for two-tier cellular networks based on a dynamic partition of the spectrum between the macrocell and femtocells. However, due to their pseudo-random nature, these two latter approaches cannot guarantee any level of QoS.

So far, the above-mentioned schemes consider only fixed transmit power for femtocells. However, some other researches focus on power control for interference mitigation. A selection of relevant works in this direction is given in the following.

In [11], the authors have proposed a decentralized strategy to allocate Resource Blocks (RBs) and regulate femtocell's transmit powers depending on their distance from the underlying macrocell. In this case, distance information should be exchanged between femtocells and macrocells to calculate the minimum and maximum power allowed for transmission.

The authors in [12] study the power loading and resource allocation problem. They propose a water filling algorithm to mitigate interference from femtocells toward macrocells, but give higher priority to macrocells, which may results in a fairness problem, especially with the increasing number of indoor femtocell users.

In [5], a decentralized model for the allocation of a modulation and coding scheme (MCS), subchannels and transmit power to femtocell users is presented. The resolution algorithm is divided into two subproblems, where RBs are assigned so as to minimize the sum transmit power using a network simplex algorithm based on a chosen MCS. However, the resolution time is of the order of one second which is very high for time sensitive applications.

Some other works dealing with power control and scheduling in macrocells using different heuristic algorithms have been presented in [13], [14].

While the above related works deal with power and resource allocation problem, none of them takes into account user's differentiation in OFDMA femtocell deployments. This is very important for network operators willing to provide different services and applications at different rates. Hence, we present in this paper a new joint power and resource allocation strategy for femtocell networks, minimizing the total transmit power and providing QoS guarantees for accepted HP users, and at the same time maximizing the throughput for BE users.

III. SYSTEM DESCRIPTION

We consider an OFDMA (e.g., LTE) femtocell's network consisting of several FAPs representing residential or enterprize networks. In such system, the frame structure can be viewed as time-frequency resource blocks (RBs), also called tiles. In our study, we focus on co-layer interference mitigation as in [3]–[5], [9], and we study the case of downlink communications. Each FAP serves a number of users. Two types of users are considered: i) HP users who require fixed QoS guarantees in terms of bandwidth, and ii) BE users with no minimum guarantee. For example, HP users can be the FAP's owner, while BE users are the visitors (in open or hybrid access); or HP and BE users can be differentiated by the price they pay for the service.

It is expected, in urban dense environment and especially during peak hours, that the sum of demands of the FAPs exceeds the available resources. Therefore, our objective is to find, for such congestion situations, an effective power and resource allocation algorithm that considers the QoS requirements of HP users and then tries to serve BE users while controlling the interference between femtocells.

In the following, we first present the notations used in our analysis, then we formulate our joint power control and resource allocation algorithm as multi-objective optimization problem.

A. Notations

- $\mathcal{F} = \{F_1, ..., F_N\}$ is the set of FAPs, where N is the total number of femtocells deployed in the network.
- $\mathcal{H} = \{u_1, ..., u_{n_{hp}}\}$ is the set of HP users.
- $\mathcal{B} = \{v_1, ..., v_{n_{be}}\}$ is the set of BE users.
- D_u denotes the demand of the user $u \in \mathcal{H} \cup \mathcal{B}$.
- $\mathcal{K} = \{1, ..., K\}$ is the set of tiles available for the network.
- Δ_u is the binary resource allocation vector for user u, with 1 or 0 in position k according to whether the tile k is used or not.
- P_u^n is the transmit power vector from FAP F_n to its user u, where $0 < P_u^n(k) \leq P_{max}$ if the tile k is used by the user u or $P_u^n(k) = 0$ otherwise. We note here that since a FAP can transmit on tile k to only one user u among its attached users, then we will alternate the notation $P_u^n(k)$ and $P_u(k)$.
- P_{max} is the maximum transmit power fixed by the network operator.
- $\Gamma_{u,k}$ is the required SINR for user u on tile k.

B. Problem Formulation

As stated earlier, our objective is to find the optimal resource allocation of a set of tiles and the corresponding transmit power in each FAP to deliver users' data, while minimizing the interference between FAPs and at the same time providing QoS guarantees for HP users as well as maximizing the throughput for BE users.

To obtain a better spatial reuse and reduce interference between neighboring femtocells, each transmission should occur at the lowest power cost, such that the required SINR value is achieved. Hence, by minimizing the transmit power, a FAP will tend to allocate to its users the tiles that are less interfered by neighboring femtocells. Moreover, if a user is closer to a FAP, it will need lower transmit power than a user on the edge. In this case, neighboring femtocells can reuse the same tiles for their corresponding users closer to them. On the other hand, edge users will need a higher transmit power than users at the center, since they suffer from high path loss. In this case, those users will be allocated the tiles that are the least interfered in the aim to minimize the total transmit power.

The expression of the received SINR for user u attached to the FAP F_n on the tile k can be given as follows:

$$\gamma_{u,k} = \frac{P_u^n(k)/pl(u,n)}{w_{u,k} + \sigma^2} = \frac{P_u^n(k)/pl(u,n)}{\sum\limits_{m \neq n} P_{u'}^m(k)/pl(u,m) + \sigma^2} \tag{1}$$

where $pl(u,n)$ denotes the path loss between user u and its FAP F_n, $w_{u,k}$ represents the interference suffered by user u on the tile k, and σ is the noise density. Note that in our case, the path loss is modeled based on A1-type generalized path loss models in the frequency range 2-6 GHz developed in WINNER [15].

Hence, our objective is to minimize the total sum of the transmit power of all users while ensuring on each tile the required SINR. On the other hand, an HP user is admitted in the network, only if the demands expressed as a number of tiles are fully satisfied. However, this QoS constraint is not applicable to BE users, who will be allocated the remaining resources after serving HP users. In this case, we introduce a slack binary vector s_v for each BE user v, where $s_v(k)$ is equal to 1 if the system fails to allocate the tile k to the BE user v (i.e., indicating the need of more resources than available in the network to satisfy its demand). Hence, our second objective is to minimize the sum of slack variables for BE users.

The joint power control and resource allocation problem for HP and BE users can be thus formulated as shown in Problem 1. In this problem, condition (a) bounds $P_u(k)$ between 0 (when the tile is not used) and P_{max}. Condition (b) ensures that the received SINR is at least equal to the required one when the tile is in use (i.e., $\Delta_u(k) = 1$). Condition (c) denotes that HP users should be fully satisfied. Condition (d) indicates the slackness of resources allocated to BE users. Condition (e) ensures that two users in the same FAP cannot use the same tile. And finally, conditions (f) and (g) indicate that $\Delta_u(k)$ and $s_v(k)$ are binary variables.

Problem 1 is a multi-objective non-linear optimization problem since the objective function is a product of two outputs. To solve it, we propose first to transform the problem into a linear one, then to subdivide it into subproblems by means of clustering. The corresponding problem will be then solved sequentially. That is, we will try to satisfy HP users first, then resolve for BE users with the remaining resources. This approach considerably reduces the time complexity of the allocation problem and implies successive provisioning steps, as described in Section IV.

Problem 1 Joint power control and resource allocation for HP and BE users

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$$\min \sum_{u \in \mathcal{H} \cup \mathcal{B}} \sum_{k=1}^{K} P_u(k) \times \Delta_u(k)$$

$$\min \sum_{v \in \mathcal{B}} \sum_{k=1}^{K} s_v(k)$$

`subject to:`

$$(a)\ \forall k,\ \ \forall u \in \mathcal{H} \cup \mathcal{B}: \quad 0 \leq P_u(k) \leq P_{max}$$

$$(b)\ \forall k,\ \ \forall u \in \mathcal{H} \cup \mathcal{B}: \quad \gamma_{u,k} \geq \Gamma_{u,k} \times \Delta_u(k)$$

$$(c)\ \forall u \in \mathcal{H}: \quad \sum_{k=1}^{K} \Delta_u(k) = D_u$$

$$(d)\ \forall v \in \mathcal{B}: \quad \sum_{k=1}^{K} \Delta_v(k) + s_v(k) = D_v$$

$$(e)\ \forall k,\ \ \forall F_n \in \mathcal{F},\ \ \forall u, u' \in F_n : \Delta_u(k) + \Delta_{u'}(k) \leq 1$$

$$(f)\ \forall k,\ \ \forall u \in \mathcal{H} \cup \mathcal{B}: \quad \Delta_u(k) \in \{0,1\}$$

$$(g)\ \forall k,\ \ \forall v \in \mathcal{B}: \quad s_v(k) \in \{0,1\}$$

IV. PROPOSAL: QP-FCRA ALGORITHM

In what follows, we describe our `QP-FCRA` algorithm for OFDMA femtocell networks. In our previous work [2], we proposed a hybrid centralized/distributed resource allocation algorithm, namely `FCRA`, based on clustering with fixed transmit power and without taking into account QoS differentiation between femto users. In this paper, we propose to integrate a power control strategy to enhance the system performance while guaranteeing QoS requirements with users' differentiation.

Similar to [2], `QP-FCRA` algorithm consists of three main phases: (i) Cluster formation, (ii) Intra-cluster resource and power allocations, and (iii) Inter-cluster resource contention resolution. In what follows, we present these three phases.

A. Cluster formation

First, each FAP will gather information of the surrounding environment by listening to neighboring transmissions via a receiver function called Sniffer [16], and by collecting measurement reports received from attached users. In this stage, a maximum transmit power P_{max} is assumed to be used by all FAPs. Based on these information, the FAP can compute the number of interfering femtocells (i.e., interference degree) and transmit it along with its Physical Cell Identity to each one of them. After obtaining the list containing interference degree of neighboring femtocells, each FAP can distributively decide whether it is a Cluster-Head (CH) if it has the highest

Problem 2 Joint power control and resource allocation for HP users

$$\min \sum_{u \in \mathcal{H}} \sum_{k=1}^{K} P_u(k)$$

`subject to:`

$$(a)\ \forall k,\ \ \forall F_n \in \mathcal{F},\ \ \forall u \in \mathcal{H} \in F_n :$$
$$P_u^n(k) \geq \Gamma_{u,k} \times pl(u,n) \times (\sum_{m \neq n} P_{u'}^m(k)/pl(u,m) + \sigma^2)$$
$$-(1 - \Delta_u(k)) \times M \times P_{max}$$

$$(b)\ \forall k,\ \ \forall u \in \mathcal{H} : \quad 0 \leq P_u(k) \leq P_{max}$$

$$(c)\ \forall u \in \mathcal{H} : \sum_{k=1}^{K} \Delta_u(k) = D_u$$

$$(d)\ \forall k,\ \ \forall F_n \in \mathcal{F},\ \ \forall u, u' \in F_n : \Delta_u(k) + \Delta_{u'}(k) \leq 1$$

$$(e)\ \forall k,\ \ \forall u \in \mathcal{H} : \quad \Delta_u(k) \in \{0, 1\}$$

Problem 3 Joint power control and resource allocation for BE users

$$\min \sum_{v \in \mathcal{B}} \sum_{k=1}^{K} P_v(k) + \sum_{v \in \mathcal{B}} \sum_{k=1}^{K} s_v(k)$$

`subject to:`

$$(a)\ \forall k,\ \ \forall F_n \in \mathcal{F},\ \ \forall v \in \mathcal{B} \in F_n :$$
$$P_v^n(k) \geq \Gamma_{v,k} \times pl(v,n) \times (\sum_{m \neq n} P_{v'}^m(k)/pl(v,m) + \sigma^2)$$
$$-(1 - \Delta_v(k)) \times M \times P_{max}$$

$$(b)\ \forall k,\ \ \forall v \in \mathcal{B} : \quad 0 \leq P_v(k) \leq P_{max}$$

$$(c)\ \forall v \in \mathcal{B} : \sum_{k=1}^{K} \Delta_v(k) + s_v(k) = D_v$$

$$(d)\ \forall k,\ \ \forall F_n \in \mathcal{F},\ \ \forall v, v' \in F_n : \Delta_v(k) + \Delta_{v'}(k) \leq 1$$

$$(e)\ \forall k,\ \ \forall v \in \mathcal{B} : \quad \Delta_v(k) \in \{0, 1\}$$

$$(f)\ \forall k,\ \ \forall v \in \mathcal{B} : \quad s_v(k) \in \{0, 1\}$$

interference degree among its one-hop neighbors; or is attached to a neighboring cluster. For more details, the reader can refer to [2].

B. Intra-cluster resource and power allocations

Once the femtocell network is partitioned into clusters, the second step is to jointly allocate resources and transmit power for all FAPs within each cluster taking into account QoS requirements and interference state of attached users. To achieve this, each cluster-member (CM) reports to its corresponding CH the required resources to satisfy its users' demands (i.e., D_u for HP and BE users attached to the CM). Then, the joint power control and resource allocation problem (i.e., Problem 1) is individually resolved by each CH every epoch δ_t, which depends on the arrival/departure process of end users residing in the cluster. In the following, we present the two steps of our approach to resolve Problem 1 for HP users first, then for BE users.

1) HP users resource and power allocations

HP users with QoS constraints should be allocated resources and transmit power in order to achieve their requirements. On each used tile, the requested SINR level should be attained to deliver the corresponding data rate with minimum transmit power. Using the received SINR in (1), the linear formulation of the initial Problem 1 for HP users only can be represented in Problem 2, shown above.

In this problem, $\mathcal{H}$ and $\mathcal{F}$ represent the set of HP users and the set of FAPs within the cluster, respectively. Condition (a) denotes that the transmit power on the tile k should guarantee the required SINR. The second term on the right hand of the inequality ensures that $P_u(k) = 0$ if $\Delta_u(k) = 0$ where M is a carefully chosen very high value. If the tile is in use ($\Delta_u(k) = 1$), then the second part of the inequality turns to zero and the $P_u^n(k)$ gets the required value.

It is worth noting that, due to the limited network capacity, if the QoS requirements of HP users within the cluster exceed the available resources then satisfying all HP users becomes infeasible. To allow the feasibility of the problem, the HP users failing to obtain their requested SINR on a given tile will not use that tile. Hence, if an HP user can not fulfill its QoS requirements, it will be blocked during the corresponding scheduling period and will not use any tile.

At the end of this process, the power and resource allocation vectors of HP users are determined. The next step is to allocate the remaining resources to BE users, with minimum transmit power and sufficiently enough to satisfy the required SINR.

2) BE users resource and power allocations

Since the BE users might accept a degradation in their demands (i.e., a lower number of allocated tiles), a minimization of the sum of the slack variables has been added to the objective function. This allows to define a single objective linear problem that can be solved with any standard Linear Programming (LP) techniques. Recall that the slack variable represents the gap between the requested and the allocated resources for BE users. By minimizing s_v, we increase as much as possible BE user's allocation with a fair proportion, as it will be shown in Section VI. The formulation of the joint power control and resource allocation problem for BE users is described in Problem 3, shown above.

In this problem, $\mathcal{B}$ and $\mathcal{F}$ represent the set of BE users and the set of FAPs within the cluster, respectively. Condition (d) indicates that a BE user v cannot use the same tile as another BE user or a previously allocated HP user in the same FAP. It is worth noting that, since the obtained clusters' size is not large (based on extensive simulations, the clusters' size does not exceed 10 FAPs), the CH resolution using a solver such as IBM ILOG CPLEX [17], converges within a short time period, as it will be shown in Section VI.

C. *Inter-cluster resource contention resolution*

Since the resolution in each CH is totally distributed, users might experience interference on some tiles from neighboring clusters. To resolve such collisions, the same mechanism as in [2] can be realized, where we use a Bernoulli distribution to resolve resource contention between users. Indeed, a FAP receiving a report of bad channel condition from a user, will decide with equal probability whether it keeps using the considered tile or releases it.

V. PERFORMANCE METRICS

We evaluate the performance of our proposed scheme considering the following QoS metrics: Throughput Satisfaction Rate, Spectrum Spatial Reuse, Rate of rejected users, Fairness and Computation time. Hereafter, we will define the above metrics.

A. *Throughput Satisfaction Rate (TSR)*

TSR denotes the satisfaction degree of a user with respect to the requested resources. For each user u attached to a FAP $\mathcal{F}_n \in \mathcal{F}$, $TSR(u)$ is defined as the ratio of the allocated number of tiles to the requested ones and can be expressed as follows:

$$\forall u, \quad TSR(u) = \Big(\sum_{k=1}^{K} \Delta_u(k)\Big)/\mathcal{D}_u \qquad (2)$$

For a network with U users, the TSR metric can be thus given by:

$$TSR = \sum_{u} TSR(u)/U \qquad (3)$$

B. *Spectrum Spatial Reuse (SSR)*

SSR denotes the average portion of FAPs using the same tile within the network. Therefore, it is defined as the mean value of tiles' spatial reuse. The SSR metric can be thus expressed as follows:

$$SSR = \frac{1}{K \times |\mathcal{F}|} \sum_{k=1}^{K} \sum_{u \in \mathcal{H} \cup \mathcal{B}} \Delta_u(k) \qquad (4)$$

C. *Rate of rejected users*

This metric represents the percentage of HP and BE users not admitted in the network during the scheduling period. Recall that, once accepted, HP users are completely satisfied, whereas for BE users, their satisfaction degree will be maximized.

D. *Fairness*

To evaluate how fairly the resources are distributed among U existing users, we calculate the Jain's fairness index [18] for the network. It is expressed as follows:

$$\beta = \frac{(\sum_{i=1}^{U} TSR(i))^2}{U \cdot \sum_{i=1}^{U} TSR(i)^2} \qquad (5)$$

E. *Computation and convergence time*

This is the time needed for the system to compute the power and scheduling allocation for both HP and BE users and converge to a stationary allocation. It takes into account the resolution time using the LP solver and the convergence time, averaged over a large number of simulations for different scenario parameters.

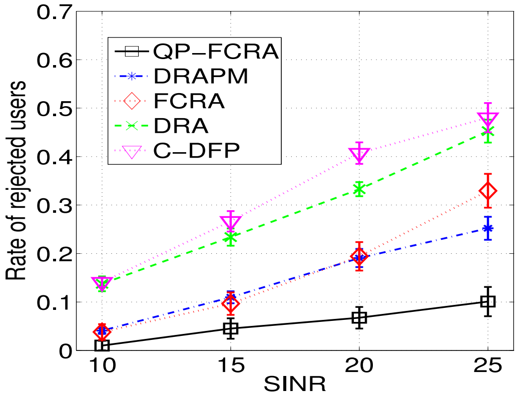

Fig. 1. Rate of rejected users

VI. PERFORMANCE EVALUATION

In this section, we evaluate the efficiency of our proposal under various interference scenarios and FAPs densities. We compare the benefits of `QP-FCRA` with respect to the `FCRA` [2], `C-DFP` [3], `DRA` [4] and `DRAPM` [5] schemes. It is worth noting that, `DRAPM` is divided into two parts: i) power and resource allocation, and ii) modulation and coding scheme adaptation. In our simulations, we only account for the first phase in order to allow a fair comparison between all schemes. We run extensive simulations to reach a confidence level of 99.70% and we calculate the mean value of performance metrics.

The reported results are obtained using the solver "IBM ILOG CPLEX" [17]. A typical downlink LTE OFDMA frame is considered, with a system bandwidth of 20 MHz and a total number of $K = 100$ tiles. We deployed two scenarios with 50 and 200 FAPs, representing low and high density networks, respectively. The FAPs are distributed randomly in a 2-D 400 m × 400 m area, consisting of 10 m × 10 m residences. Users are distributed uniformly within the residence with a maximum number of 10 users per FAP. The number of users, their traffic demands as well as their locations are varied at each simulation. These users are divided into 4 HP users and 6 BE users in the case of `QP-FCRA`. Each user generates its traffic demand, which is translated into a number of tiles. We considered different minimum required SINR thresholds: 10, 15, 20 and 25 dB to show the channel condition impact on the evaluated metrics. In what follows, we present the corresponding simulation results.

1) Rate of rejected users

Fig. 1 shows the rate of rejected users for the 200-FAP network case using the above-mentioned allocation schemes. From this figure, we can see that in low interference levels, `QP-FCRA` serving both HP and BE users has a rejection ratio of less than 1%, compared to 3% for both `FCRA` and `DRAPM`. However, this ratio exceeds 12% for both `C-DFP` and `DRA`. On the other hand, for high interference levels, the two latter schemes reject more than 45%, and `DRAPM` more than 25%, comparing to `QP-FCRA`, which is still below 10%. This is due to the fact that `QP-FCRA` accounts for users' QoS requirements when distributing the available resources, as opposed to the other schemes, where no QoS is supported.

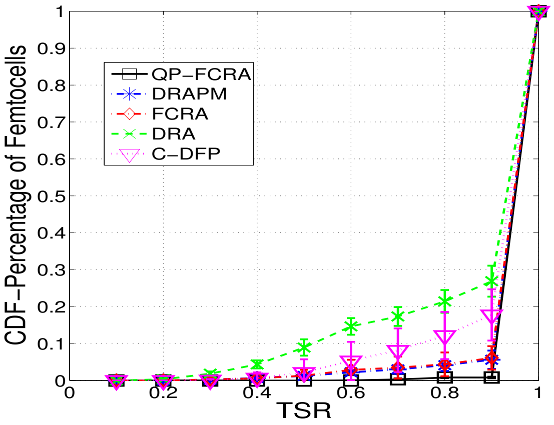

Fig. 2. CDF of throughput satisfaction rate in low density networks, SINR = 25 dB

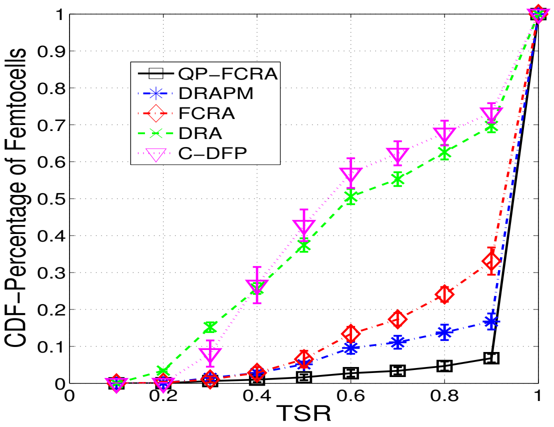

Fig. 3. CDF of throughput satisfaction rate in high density networks, SINR = 25 dB

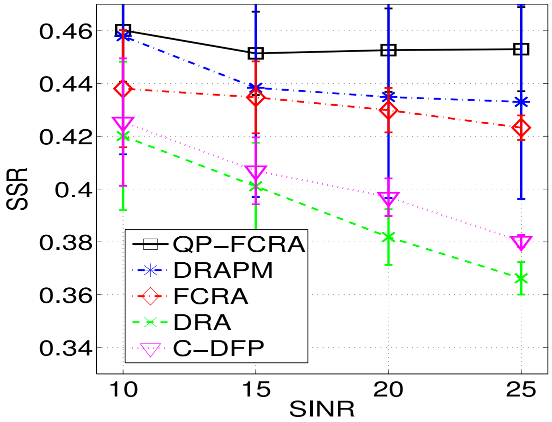

Fig. 4. Mean SSR in high density networks

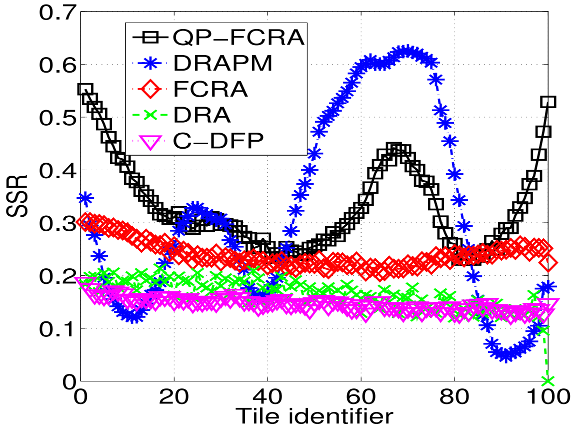

Fig. 5. SSR per Tile, SINR = 25 dB

2) Throughput Satisfaction Rate (TSR)

Fig. 2 plots the cumulative distributed function (CDF) of the throughput satisfaction rate, for low density networks in the high interference level case. We can observe for `QP-FCRA` the improved performance compared to the other solutions. Indeed, for the `DRAPM` and `FCRA` schemes, more than 95% of femtocells have their $TSR \geq 0.9$. With `QP-FCRA` it is improved to more than 98% while this ratio degrades below 80% for `C-DFP` and `DRA`.

In high density networks, the observation is more clear. In fact, as shown in Fig. 3, while for `QP-FCRA`, 92% of femtocells have their TSR above 0.9, for `DRAPM` and `FCRA`, this ratio decreases to 80% and 70%, respectively. `C-DFP` and `DRA` degrade below a ratio of 30% of femtocells able to achieve the same rate. This is due to the high number of constraints for `C-DFP` in high network density and the use of a random hashing function for `DRA`, without power control, which results in performance degradation.

3) Spectrum Spatial Reuse (SSR)

Fig. 4 plots the mean spectrum spatial reuse of the underlying schemes as function of SINR thresholds for high density networks. We can clearly observe, with the integration of power control, a much higher spatial reuse. Indeed, when $SINR_{th} = 25\ dB$, it reaches around 45.5% with `QP-FCRA` compared to around 43% for both `DRAPM` and `FCRA`, while this ratio is around 37% and 38% for `DRA` and `C-DFP`, respectively.

Fig. 5 further investigates how each tile is reutilized in the network. It shows the reuse rate of each tile k $(1 \leq k \leq 100)$ for the 200-FAP network case with $SINR_{th} = 25\ dB$. While `QP-FCRA` and `DRAPM` reach nearly 60% of the reuse rate on some tiles, `FCRA` is around 30%, and both `DRA` and `C-DFP` are below 20%. We can also observe how for the `QP-FCRA` and `DRAPM` schemes the distribution varies, showing the adaptation with the channel condition, as opposed to the other solutions. However, we note that `QP-FCRA` outperforms `DRAPM` for almost 60% of the given resource blocks (i.e., when $k \leq 40$ and $k \geq 80$).

4) Fairness

The Jain's Fairness Index calculated as the average for all the network is shown in Fig. 6. Note that it reaches 1 in the best case, where all users are fully satisfied. As we can observe, even for the worst case scenario (i.e., high interference level and high density network) the fairness is around 0.99 with `QP-FCRA`, compared to approximately 0.92 and 0.93 for `DRAPM` and `FCRA` respectively, but it decreases to below 0.77 for `C-DFP` and `DRA`.

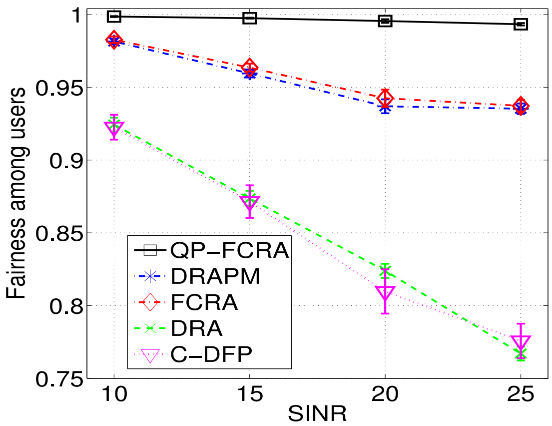

Fig. 6. Fairness comparison

This is likely thanks to the power control mechanism that avoids penalizing users that suffer from high interference and with high demands.

5) *Computation and convergence time analysis*

Last but not least, it is important to assess if the overall good performances of `QP-FCRA` comes at the expense of a higher time complexity compared to other schemes. Table I reports the computation and convergence time needed for `QP-FCRA`, with respect to `FCRA`, `C-DFP`, and `DRAPM` to resolve the resource allocation problem.

We can observe that `QP-FCRA` needs more time than `FCRA` since the latter does not integrate power control. However, the computation and convergence time remains very low below 77 milliseconds and 108 milliseconds for the low and high density networks, respectively. On the other hand, `DRAPM` which includes power control but is totally distributed, computes the algorithm fast but takes much more time to converge. As we can observe, the total time needed to compute and converge is around 1 second for the low density network, and about 1.3 seconds for the high density network. With `C-DFP`, it is worth mentioning that the probability to generate the optimal solution is inversely proportional to the network size. Indeed, as shown in our previous work [2] and based on extensive simulations, the probability of finding the optimal solution is equal to 1 if the number of FAP is low (i.e. $N \leq 20$). However, in a high density network (i.e., $N \geq 100$), this probability becomes roughly null. That's why in our simulations, the solver is stopped after 6 seconds.

VII. CONCLUSION

In this paper, we proposed a new scalable and fast computing joint power control and resource allocation algorithm for OFDMA femtocell networks, named `QP-FCRA`, based on clustering. It takes into account users' QoS requirements and minimizes the transmit power for each femtocell, alleviating thus the interference between femto users. We differentiated between high priority and best effort users and considered a cluster-based hybrid strategy as an alternative to centralized and distributed approaches. We have shown through extensive simulations, the performance and the effectiveness of `QP-FCRA` compared to the solutions mentioned in the state-of-the-art. We studied different network topologies, under various interference scenarios and network densities. The results have shown that our new approach improves considerably the number of accepted users in the network, the fairness of the system, the throughput satisfaction rate, as well as the spectrum spatial reuse. We also emphasizes on the scalability of our approach and the low computational time allowing the practical deployment of femtocells in low and high density networks.

TABLE I
COMPUTATION AND CONVERGENCE TIME (IN SECONDS) OF QP-FCRA, FCRA, DRAPM AND C-DFP METHODS, SINR $= 15\ dB$

Network size	50	200
`FCRA`	0.013 ± 0.003	0.07 ± 0.01
`QP-FCRA`	0.077 ± 0.03	0.108 ± 0.05
`DRAPM`	0.942 ± 0.02	1.348 ± 0.04
`C-DFP`	1.59 ± 1.0	6.80 ± 0.09

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